Pathways for scale and discipline reconciliation: current socio-ecological modelling methodologies to explore and reconstitute human prehistoric dynamics

Mehdi Saqalli, Tilman Baum

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Mehdi Saqalli
CNRS, University of Toulouse 2 Jean Jaurès, GEODE, 5 Allées A. Machado f-31058 Toulouse, France

Tilman Baum
University of Basel, IPNA,, Vogelsangstrasse, 20, D-72144 Dusslingen, Germany

Abstractð This communication elaborates a plea for the necessity of a specific modelling methodology which does not sacrifice two modelling principles: explanation Micro and correlation Macro. Three goals are assigned to modelling strategies: describe, understand and predict. One tendency in historical and spatial modelling is to develop models at a micro level in order to describe and by that way, understand the connection between local ecological contexts, acquired through local ecological data, and local social practices, acquired through archaeology. However, such a method faces difficulties for expanding its validity: It is validated by its adequacy with local data, but the prediction step is unreachable and quite nothing can be said for places out where. On the other hand, building models at a far larger scale, for instance at the continent and even the world level, enhances the connection between ecology and its temporal variability. Such connections are based on well- founded theories but lower the ñsmall causes, big effectsò emergence corresponding to agent-based approaches and the related inherent variability of socio-ecological dynamics that one can notice at a lower scale. We then propose a plea for combining both elements for building large-scale modelling tools, which aims are to describe and provide predictions on long-term past evolutions, that include the test of explaining socio-anthropological hypotheses, i.e. the emergence and the spread of local social innovations.

1 INTRODUCTION

Reconstituting human past dynamics over a landscape or a territory is more than challenging:

- Modelling is a scientific methodology but also a *de facto* constructed agreement procedure among a group of scholars from different disciplines about the functioning of a society, an environment and their interactions. It is thereby subject to points of view, assumptions and considerations which, in such a comparatively low data modelling context, are difficult to counter-argue;
- It is nearly impossible to evaluate the importance of uncertainty and random events in the course of real history. One should acknowledge that any formalization of a historical reconstitution is actually the formalization of the average and most probable history within specific conditions, hypotheses and scenarios. Extraordinary environmental events, intra-society dynamics and breakouts are thereby impossible to reposition on their right time position. Nonetheless, a reconstruction of the complex system formed by man and his environment can help us to knit a web out of the loose ends of archaeological research.

This article describes several major modelling approaches with regard to past coupled human-environmental dynamics, with their specific strength, drawbacks and difficulties, thereby illustrating the scale gap we would like to illustrate. Thus we elaborate the methodological and epistemological orientation we plea for.

2 MODELLING PAST RURAL ENVIRONMENT-SOCIETY SYSTEMS

2.1 Distinguishing modelling objectives, subjects and objects

Following Lieurain (1998), Garneau and Delisle (2002) or Bousquet and le Page (2004), three goals are assigned to modelling strategies: describe, understand and predict. As it is the fate of archaeology to draw conclusions on a sometimes very narrow database, it is necessary to continuously develop and adapt models to conceptualize most probable historical scenario proposals, i.e. eliminate least-probable ones. A second benefit of the modelling procedure is the identification of the driving forces and key elements of the simulated system. This is possible, because a wide range of historical scenarios may be reconstructed by varying certain input parameters. It can then for instance eliminate too simplistic or less plausible ones, such as the one ñsingle cause Armageddonò cliché (climate, volcano, flood). As a third step it may be considered to validate theories and make predictions on the results of interacting system elements. Finally, following Edmonds and Moss (2005), this global « descriptive » methodology (considering that, without any previous analysis, one cannot determine which variable can be considered as negligible) can allow to display a simplified version of a reconstructed historically plausible scenario, i.e. to produce a series of theoretical models, each one corresponding to a ñdigestedò research question, dedicated to the exploration of the possible variations of one or maximum two factors.

This trend of modelling the past is highly promising because it will help to solve large and theoretical questions, once parameterization and calibration have been established robustly to avoid the questioning over assumed postulates. One of the most famous simulations of the past, "Understanding Artificial Anasazi" can be

categorized into such a scheme at a local ñterroirñ[1] level: from a study (Kohler and Carr 1996), several theorized modelling experiments were assessed (Dean et al. 1999; Axtell et al. 2002; Janssen et al. 2003; Janssen and Scheffer 2004; Kohler et al. 2005; Kohler 2008; Janssen 2009; Kohler et al. 2012; Crabtree and Kohler 2012).
Moreover, and following Landais and Deffontaines (1987), a model is a ñtheoretical and finalized representation of a reality formulated on the basis of situated observations, of a predefined framework that will then be applied to study cases and permits to give representations quicklyò. A model serves to establish structural relationships and functions existing between the factors that one would like to analyse, and their respective importance (Parker et al. 2003). All models are designed for reaching a goal, an objective that can be problem solving, decision-support or simply experimentation (Boy 1992; Le Bars 2003)]. This definition adopts an operational standpoint, thereby insisting on the subjectivity and the need for an objective for every model. In our case, this should establish what research question is investigated with a model, i.e. what research subject and what research object is considered:

- If the subject is the history of the impact of the human expansion over an area, which can be either the Earth itself, a portion of it or a ñterroirò, the studied object is the area, including the related natural resources, from which humans are seen solely as a transforming force, whatever the refining of the behaviour of this force can be (inclusion of innovations, etc.). The main use of such models is in environmental disciplines.
- If the subject is the history of the population itself and the impact of the environment over its evolution (again regardless of its size), environment and related natural resources should be considered as an influencing force, even if humans themselves transform the capacity of this force, and the research object is the population itself. The main use of these models is in (pre-) historic disciplines.

2.2 Agent-based modelling distributed simulation: an adequate tool for modelling villagers and fields

Humans form complex groups and societies that are bound to their environment in more or less intense interactions, the imprint of which are found in landscapes. One may note that this dependency on the environmental context and natural resources allows scientists to better feature and frame the field of potential evolutions of a rural society than of an urban society, because the evolution of the latter is less bound to direct environmental constraints, explaining thereby that most archaeologically related investigations using models focus on rural societies.
Thus, archaeological/palaeo-environmental models can either directly analyse the social interactions between agents, or use the landscape as a reference plane. The choice of the adequate modelling technique is strongly dependent on the research question, and in many cases also on the scientific background of the modeller. In any case, it is the mutual interdependence of humans and their environment that is in the focus: environment and natural resources are quickly and directly affected by human activities and at the same time, humans are directly and rapidly affected by the availability of natural resources. We see here the interest and the efficiency of agent-based modelling tools. In the Neolithic, power processes creating a public policy resulting in a large transformation of the access to and/or the nature of natural resources did not exist.ò Instead, such interactions are atomistic, i.e. they correspond to the repetition of small and direct transformations and uses of a territory at a lower spatial scale because of one or a small group of humans. De facto, they correspond well to the distributed way of conceiving large transformations of a landscape by repetitions of actions played by a multitude agents and actors that multi-agent modelling are the best to deal with. However, the large debate between descriptive and theoretical models initiated by Edmonds and Moss (2005) does have impact on the way multi-agent modelling is used for studying archaeological/palaeo-environmental issues.

2.3 Scales and discipline drivers: categorizing which model you are working on

While a modellers' dream can be to construct global models that integrate data of all relevant research disciplines, more local reconstructions with a narrower focus are better suited to meet the needs of local to regional heritage management. The model census we have assessed non-exhaustively may lead to a classification of these models in four categories, different in their scale and drivers. They may roughly be presented following a matrix of categories combining scales on one hand and disciplines used as inputs and drivers in the other hand:
i. Scales:

a) The level of the village/hamlet (defined here along the more adequate word ñterroirò) unit is often used because it is the functional unit of management of a landscape, the geographic expression of a combination of rationalities that have to interact altogether. Building a model of one simulated entity below this level is impossible regarding the importance of such interactions, both direct (marriages & other social interactions but also mutual manpower support for instance). Roughly, it is the level in which micro-economic rationality can be considered in order to analyse and explain differences in the use of natural resources;
b) The level of the territory that corresponds to a culture or a group of cultures. Roughly, it is the level in which macro-economic rationality can be assessed, assuming a certain homogeneity regarding the use of

[1] The French word "terroir" is defined both geographically (the set of space managed and exploited by a village community: [5]) and socially (a socially defined territory containing a set of resources and associated rights to these resources: [6]). It is therefore a geographically defined territory, but whose definition is social: it is the geographical framework of life of a rural society. It is important to specify for the land tenure issue that the "terroir" is defined on the basis of usufruct and not of property.

natural resources within this culture comparing to others. A main aspect here is to analyse the impacts of a homogenous use of these resources;

ii. Involved disciplines and drivers:
   a) Archaeology and social science is used as the major input for the model and the expected results are focussing on palaeo-environmental issues;
   b) Paleo-environmental data are used as the main inputs for the model and the expected results are focussing on archaeological issues.

2.4 Genericness criteria: analysing the validity extension methodology

Finally, we introduce a classification of different genericness criteria that models tend to achieve. In contrast to the binary categories of scale- and discipline-we describe above, (a model is either built on a rationality on a global scale, then tested on a lower scale - or the opposite; but cannot be both; a model uses disciplines as inputs and cannot therefore use the same inputs in a validation step), these genericness criteria are gradients on which one can position its model:

1. The social and environmental spatial genericness: The accuracy of fit possible when using local environment data and locally evidenced farming practices can hardly be generalized for a spatially broader model extent: one is then forced to establish adaptation ñrulesò of this modelled production system, thereby implying hidden or formalized rules regarding human rationality (securization, maximisation, constraints-based sequential rationality, etc.);
2. the social-temporal genericness (innovations, adaptations, social evolutions): The very same problem concerning space may be applied regarding time as well: one may have to introduce evolutions of techniques, practices and/or social relations that can adapt themselves along simple (reactive, elimination) or complex procedures (learning, cognitive adaptation, etc.) to get out from the ñinstantnessò of these models;
3. The Micro adequacies: local emergences and social differentiations. Following Fraser (2003), Misselhorn (2005) or de Sardan et al. (2007)], once a famine or any other plague occurs, they affect only portions of the population (families, groups), mainly the most fragile ones, and not the whole population. This means that only very specific and catastrophic ñplaguesò (for instance well-referenced and very harsh droughts), may constrain simulated populations because they affected the whole population (see Dean et al. (1999);Axtell et al. 2002; Janssen et al. 2003; Kohler (2008) on the Anasazi collapse). More generally, any social and economic dynamic may not be seen as affecting indifferently a whole population, but only portions of it, combining specific parameters (for instance at the level of a family, lack of manpower, low cropping surface per capita, bad gender repartition regarding inheritance access, etc.).

One can then position a model´s genericness extent and build its validity extension along these genericness criteria.

3 MODELLING ENVIRONMENTALLY-CONSTRAINED BUT ADAPTABLE SOCIETY-ENVIRONMENT SYSTEMS

3.1 TEM (ñTerroirò-based environmentally constrained models

Following our classification, we describe here the ñterroirò level models, where a society and its evolution is driven by their calorie and resource demand and constrained by environmental parameters. Important information used for the model originates in archaeology, such as tools and practices; knowledge on environmental factors is also important.

As an example of these models, Baum (2014) has formalized a GIS-based object model based on information from available and relevant literature and local archaeological data regarding environmental characteristics (soil, vegetation, local climate, distance to village) and cropping and livestock-keeping practices, to evaluate the environmental impact of human settlements over several village territories, along several farming scenarios

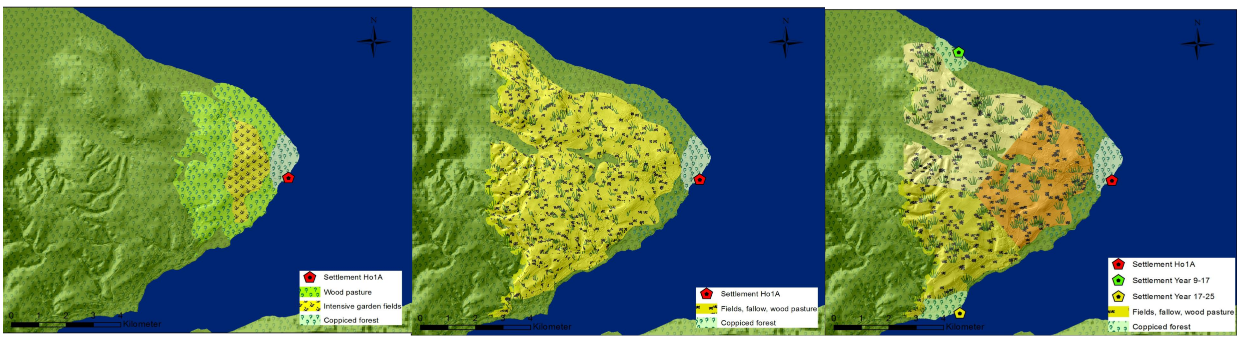

Fig. 1:Three ñsnapshot modelsò illustrating the model design in (Baum 2014). Economic areas are calculated using various hypotheses and their extent modeled in a GIS. LEFT: Intensive Garden Cultivation is applied, resulting in permanent, fields and ñextraò wood pasture(light green); CENTER: Shifting Cultivation is applied, a large area is affected in 25 years. The resulting area exhibits elements of fallows, coppiced stands, and livestock browsing areas side by side. RIGHT: Two hypothetical settlements (green and yellow) have been added, and a relocation of the sites is assumed after 8 years. This might reduce maximum travel distances for agricultural activities.

(shifting, intensive garden and non-intensive cultivation) and diet assumptions. (Figure 1)

Further works with similar research interests include Coolen (2010), who has worked over different sites of the LBK (Linear Band Keramik) culture territory in Europe: thanks to a systematic geographical census of the archaeological sites of the LBK culture over a region, the agro-ecological characteristics of the implantation sites of this culture (pedology, climate, orientation, hydrology, relative distance to other sites) can be statistically determined. Combined with estimates on economic and agriculture-related parameters of this agropastoral system, this methodology aims at establish a spatial discrimination of a territory along site preferences and potentialities according to a specific culture agropastoral habits. This methodology is equivalent in Burke et al. (2008); Tipping et al. (2009); Graves (2011); Carrer (2013). For instance, Yu et al. (2012) test on the Yiluo valley a combination of demographics and agriculture-based extrapolations and social assumptions based on what archaeology but also modern information provides.

Following their work on Swiss and German archaeological sites, Ebersbach and Schade (2004) have studied livestock-keeping needs and consequences on sustainability of environmental resources and livestock-based farming societies: through a GIS, they have estimated the impacts on an extended village territory of the necessary livestock to both feed the population and manure the fields that are necessary for crop production for feeding a population.

The research object of all these simulations is the area or the evolving landscape; the major tool is GIS input data comprise archaeological and paleo-environmental information. However, because the subject, i.e. the research question, differs, they are representative of the ñdiscipline-as-inputò factor differentiation: Coolen (2010) used environment as input and deduced site potentialities, with the hope that further archaeological excavations may provide confirmation. Baum (2014) and Ebersbach and Schade (2004) used archaeology as input and deduce the impact on the related territory and natural resources following various scenarios. These approaches are used to test the relevance and implication of certain model parameters, such as the crop husbandry or the size of the economic territory They set up spatial hypotheses which serve for explanatory purposes and as a reference plane for future works. The strength of such models is to estimate the constraints in which agro-socio-systems may evolve using local data and archaeological and/or agro-environmental assumptions on economic activities. Meanwhile, many of them establish the maximum potential level, i.e. a carrying capacity equivalent in those specific conditions and techniques such a society may reach, but not its fragility regarding social variables and temporal ñcoincidencesò that are inherent to every society.

*3.2 WEM: **ñ**World**ò** size environmentally constrained models*

Modelling prehistoric and pre-industrial society-environment systems is essential to understand the co-evolution of climate and humans over recent Millennia as well as the current state of the earth system. Such an analysis should be settled at the global scale, simply because it is the sole relevant scale for apprehending human-induced climate changes. Many of the ecosystems that are highly valued today for the services they provide to humanity are the result of long-term interactions between society and their environment. Because detailed observations of these interactions will always be limited in space and time, global human-environment models may be useful tools to bridge spatial and temporal gaps in data and to test hypotheses about the large-scale development of society and the environment.

Despite its promise, global modelling, however presents several additional challenges compared to the ñterroir scaleò described above. The foremost among these challenges concerns data both for driving the models and for evaluating their output. Outside of Europe and parts of East Asia, critical information on subsistence lifestyles, the timing of key transitions, and on paleo-demography needed to parameterize models is not available because of a lack of investigations in these regions or a poorly preserved archaeological record. Likewise, palaeo-environmental and ethnographic information, that is highly valuable for model evaluation, is largely absent from many continents where geographic conditions and local history led to poor preservation of archives, both natural and human.

Regarding the three points described in section 2.4, WEM-type models obviously meet the spatial genericness criterion (1) but they methodologically do not completely fulfil the criterion (2) regarding time: rules of the model do apply all along simulations but the model lacks time-related adaptability. Finally, the criterion (3) is not answered as such models do belong to the ii.b) palaeo-environmental ñDisciplines used as inputs and driversò scheme meaning that changes are environmentally driven.

Nevertheless, there are several promising methodologies that are currently being applied to understand society-environment systems at global scale. These models may be roughly divided into two categories:

- data-driven approach where demographic and subsistence data are inputs to the model;
- an ñorganicò approach, where the model simulates potential human population and subsistence lifestyle as prognostic variables. Both of these approaches have advantages and disadvantages and are currently under rapid further development.

The data driven approach is typified by the ALCC scenarios KK10 (Kaplan et al. 2009; 2011)and HYDE (Goldewijk et al. 2011). These scenarios are the result of empirical models that take geographically distributed estimates of population at any time in the past and combine them with information on climate and soils in order to estimate the magnitude and spatial distribution of land use. The models used to generate these scenarios assume subsistence lifestyle implicitly, i.e., everyone on earth at a given time is presumed to have the same type of subsistence strategy. While HYDE makes a simplistic distinction between land use for crop or pasture based upon present-day geographic patterns of land use, it does not consider changes in per capita land use over time (intensification). In contrast, KK10 models intensification as a non-linear function of population density itself, so that low population densities use relatively large amounts of land. This difference in the representation of per capita land use among the models leads to very large differences in the global pattern of land use in the past (Figure 2).

As noted above, neither model takes directly into account the way in which different subsistence lifestyles may use the same landscape, e.g., foragers vs. shifting cultivators vs. permanent agriculturalists vs. pastoralists. This distinction among land use types, in particular the shift from foraging to farming, may be critical for understanding the pattern of land cover change and human impact on the environment during pre-industrial time. While the agricultural transition could be prescribed in models based on archaeological records, lack of investigations or well-preserved sites implies that in many parts of the world prescription would be based on guesswork or assumptions. An alternative approach is to use a model that explicitly simulates subsistence lifestyle changes, as in the ñorganicò approach mentioned above.

Currently the best example of this approach that has been developed and applied at continental to global scale is the GLUES model (Global Land Use and technological Evolution Simulator (Lemmen et al. 2009). GLUES simulates human population density, technological change and agricultural activity directly, based on the concept of gradient adaptive dynamics, where adoption of a subsistence lifestyle, e.g., Neolithic agriculture, by any given group of people at any particular time depends on endogenous environmental and social factors, e.g., potential productivity, population density, and exogenous factors, including the presence of farming people in neighbouring regions. Simple rules in GLUES, including continent size and climate, allow the model to simulate the spontaneous transition to farming in certain regions of the world (Lemmen and Wirtz 2003).Once farming is established, the model simulates the advection of peoples and diffusion of ideas and technology across environmental gradients. The GLUES model is driven by static maps of potential productivity and climate on regions of ca. 1000 km2 that are defined as areas of relatively homogeneous climate and productivity. GLUES can further use information on climate variability prescribed as discrete events in space and time to influence human activities and populations. GLUES´ prognostic outputs include population density, relative proportions of farming people in the region, and the level of technology used by the farming people. The major disadvantage of GLUES is that it may produce histories of society-environment interactions that are at-odds with reality, e.g., the spontaneous development of agriculture in places where it is not known to have occurred. Additionally, GLUES in its current form cannot simulate major technological transitions beyond the initial adoption of agriculture, e.g., metallurgy, urbanization, or the development of complex societies, with focuses on specific sites such as Western Europe (Lemmen et al. 2011) or the Indus civilization (Lemmen and Khan 2012).

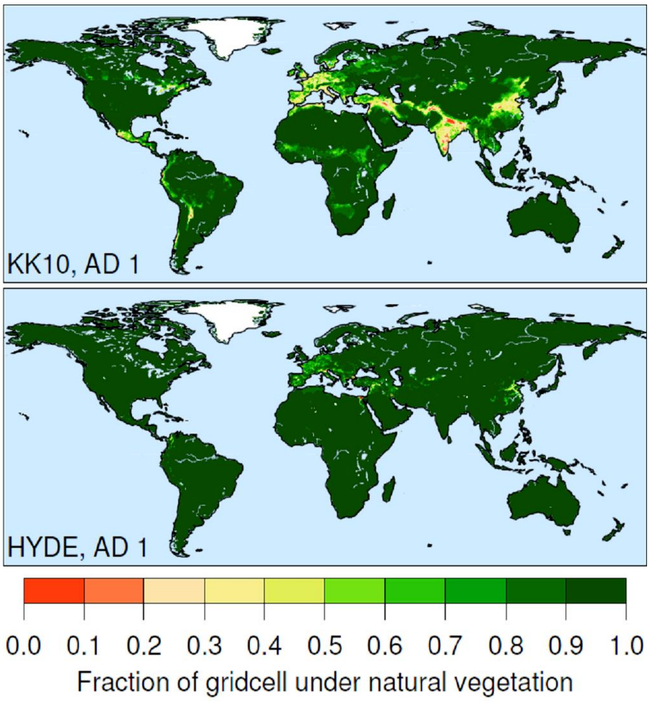

Fig. 2. Comparison between global anthropogenic land cover change scenarios KK10 and HYDE for the year AD 1. The large discrepancy between the scenarios in the maps is caused by differences in the treatment of per-capita land use. HYDE fixes the spatial pattern of per-capita land use observed in AD 1961 for all time periods in the past, whereas KK10 models per-capita land use as a function of population density, with intensification occurring at higher densities (courtesy of J. Kaplan)

Such models answer the criteria (1) and (2) with a formal justification of the appearance of such technical innovations (Lemmen 2012). More globally, they cannot answer the criterion (3):

- Social innovations, such as socio-anthropological family evolutions and/or political structures, are less likely to be modelled, while such social innovations may have a determining impact on the ñcapacityò of a society for conquering new territories, following non-Malthusian hypotheses (Boserup 1965; 1976; Lemmen 2012)[. For instance, Todd (2011)has suggested large variations of the family structures in Eurasia, linked

with the appearance of unequal families and the consequences on the culturesô differential ñcapacityò of expansion.
- The effects of ñcoincidencesò, i.e. emergences may disappear as such conjunctions are smoothed while going at a broader scale, both socially and spatially.

4 MODELLING INNOVATIVE SOCIETIES IN ITS ENVIRONMENT

*4.1 TSM: **ñ**Terroir**ò**-based society-driven models*

The focus on technical and/or social aspects of changes at the local level has been studied as well. Meanwhile, tending to answer the combination of criteria (1) and (3) (social-environmental genericness on one hand, and innovations and differentiations on the other hand), such studies are de facto related to a KISS approach [4] for this specific question:

- The first possibility are theoretical KISS models, through which a question on innovations and conflicts is analysed (Bentley et al. 2005; Younger 2011)
- The second possibility, KIDS, is more focused on local situations on which many data and information are available and build some archaeological and/or socio-anthropological hypotheses to test, with the model as the test bed for various social and/or technical scenarios (Allen et al. 2006; Altaweel, 2008; Murphy 2012; Rogers et al. 2012).

One of the major developments on modelling past local ñterroirsò concerns the Anasazi people in the Southwestern United States. The innovation there was to include social factors along with environmental ones for modelling a ñterroirò (Kohler et al. 2005; Kohler 2008)]. However, the advantage of describing an ñislandò territory, i.e. a closed system where no influence from outside may be considered, faced the default of this ñislandò situation: droughts did have such a huge impact that they overcame all social configurations. Such a modelling project may be more effective in study sites where environment is not a so blatant challenge.

Saqalli et al. (2014) describe another spatialized Agent-Based model, which aims was to reconstruct the LBK farming and society system functioning at the village level. The idea was to reconstruct in the same model the functioning along a very local grid level (1ha/ cell) of village societies. The goal of this combination of scale was that small variations at the farming/livestock keeping/hunting-gathering system do have exponential effects on a larger scale.

Because the purpose of this model was to raise hypotheses on socio-anthropological and economic organisations and was dedicated to analyse its impact on the environment, it takes for granted biophysical aspects and tends to integrate and combine environmental rules from literature and available data through inference: The use of databases from the European Commission provides the access to present-day soil characteristics (pedology and elevation), from which was deduced the pedology of the LBK period, following the soil retro-evolution methodology assessed by Schwartz et al. (2011). Within this simulated environment, family organisation and manpower availability are settled along with what archaeology and palaeo-analysis provides on the past farming system possibilities (for instance, family size can grow beyond mononuclear families, reconstituting thereby LBK houses and households, larger than Starçevo houses). Together with inferences from present-time agronomy and zootechny that both constrain the possible combinations of the farming system (for instance, the permanent fields), such a model may be used for testing hypotheses on the functioning of this past society. Similar models were built with the integration of demographic and social issues along environment, with environment and natural resources shortages and stresses as inputs and variable impacts on the population evolution and differentiation as outputs (Wilkinson et al. 2007; Verhagen and Whitley 2012)).

The model is conditioned by food requirements and the demand in non-finite resources (firewood, timber, cultivable soils, livestock pasture or forests, hunting and gathering grounds) of individual households with household members varying from 1 to Ð (mean: 5 to 7) but is driven along time according to family social organization & individually randomized dynamics. A first version of the model was settled using the CORMAS platform, written in Smalltalk and focusing on smaller territories of 20 * 20 km, i.e.. 40 000 1 ha pixels, of four typical LBK sites (Aisne valley in France, Aldenhoven & Hesse in Germany, Melk in Austria). The size of this small version of the model is big enough for allowing further household and village settlements after the first site building, depending on family splitting and departure rules (local ultimogeniture, patrilocality, choosing no side-effect inheritance) and then reconstructing the agglomerate-shaped expansion process.

This model should be considered as a scenario testing platform. 12 variables were considered (for instance, initial population, site choice procedure, colonization procedure, family organization, presence/absence of Mesolithic hunters-gatherers, integration of climatic variations according to the European Pollen Database), with 2 to 3 possible "alleles", inducing 108 864 combinations to explore. However, building such a model based on the inevitable assumption of a common complex of society rules faces the obvious critique from archaeologists that such an assumption cannot be applied on a so vast territory such as the LBK extent. More globally, one may question the genericness that formally comes from other sources and societies: Applying such hypotheses onto a past society implies considering them as generic and thereby applicable to broader spatial territories and cultures of the same period. Through this assumption, we raise the question whether the extension of any socio-ecosystem model from very local sites to global areas may be valid at all, i.e. is it possible to fulfil the criterion 1.

Another example of this model category is presented in chapter xx of this book. WELASSIMO is an Agent-Based Model simulating land use of Neolithic wetland settlements in the Swiss and German pre-alpine forelands (see Chapter xx in this book and Figure 3). The archaeological background are prehistoric lake-shore and peat-bog settlements (Menotti, 2004; Matuschik and Strahm, 2010). These sites have been characterized by waterlogging and anoxic conditions for Millennia, which is the reason for two factors that allow for highly detailed reconstructions: extraordinary taphonomic conditions that yield evidence of economic activities, and the potential of absolute dating via dendrochronology (Billamboz 2014). Numerous publications elaborate on the environment of the sites (Schibler 2006; Jacomet 2006), dietary habits (Ebersbach 2003), economic and husbandry strategies (Baum 2014), and the high internal dynamics during the early phase of the wetland settlement in the 4th Millennium BC. (Ebersbach 2010).

None of these models, however, is capable of dynamically investigating the functioning and the limitations of the coupled socio-natural system. It is the aim of WELASSIMO to fill this gap and, more specifically, to answer the following questions:

- What implications and systemic feedbacks go alongside with the published hypotheses on land-use systems?
- What was the spatial and temporal availability of non-finite resources?
- Can excessive resource use have caused the observed dynamic settlement pattern?

The Model is written in NETLOGO and is driven by the calorie requirements and the demand in non-finite resources (timber, cultivable soils, livestock pasture, and hunting and gathering grounds) of individual, standardized households (n=1-20) consisting of 6 persons. These are grouped in a hypothetic settlement located in a dynamic model environment comprising of raster grid cells of 25*25 m. The grid has been generated in a GIS and contains information on the assumed Neolithic soil type based on modern soil data (LGRB 2013), information on elevation and slope based on LIDAR-data (© LGL Baden-Württemberg), and on the assumed forest type in the Neolithic as a function of the aforementioned information and external pollen data (Lechterbeck 2001; Rösch 2014). In NETLOGO, the static forest cover information is made dynamic using modern data on development phases of primary deciduous forest (Bernadzki 1998; Bobiec 2012). In combination with the assumed forest type, these have large implications on the cells´ quantity of suitable timber and on the value for livestock forest pasture and for gathering wild plants. Both the husbandry strategies and the composition of the diet are options to be set before each simulation. The former are grouped in 4 scenarios spanning various possibilities of intensity and mobility: Shifting Cultivation (SC), Non-intensive Cultivation (NIC), Integrated Forest Horticulture (IFH) and Intensive Garden Cultivation (IGC). The latter typify different scenarios on the relative proportion of vegetable vs. animal foodstuff, of collected vs. cultivated plants, and of hunted/fished vs. domesticated animal foodstuff. When the simulation is started, the subsistence activities of the households are performed in annual time steps. According to the chosen specifications, three important outputs are observable:

- The formation of a cultural landscape in a hypothetic, ñnaturalò environment
- The implications of the chosen specifications in terms of the security of calorie supply and
- The area necessary for meeting the calorie and resource requirements of the households.

In contrast to previous models of human land use in the wetland settlements (Baum 2014; Gross et al. 1990), WELASSIMO is embedded in a dynamic framework and is therefore able to simulate feedbacks between land use

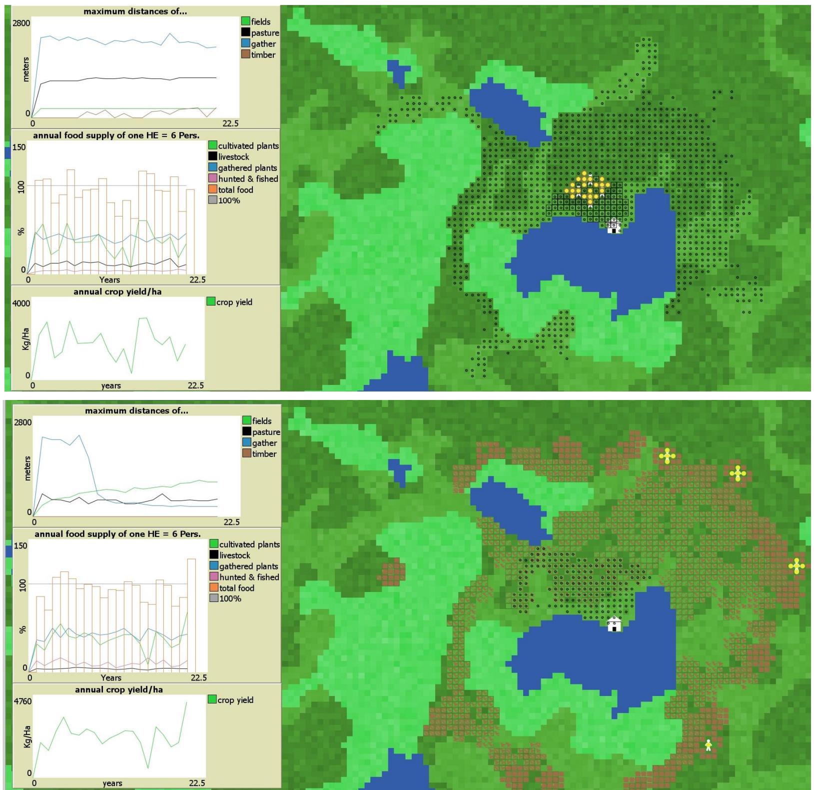

Fig.3: Two simulations illustrating the design of WELASSIMO. Top: 4 Households with 24 persons applying an intensive crop husbandry method with intensive use of manure. A large herd is necessary to produce this amount of dung, requiring a large area to feed on (patches with black dot). Bottom: same configuration as above, but applying an extensive crop husbandry method using a burning procedure. Land requirements are larger than above due to annually shifting fields. Less livestock is needed, as fields are fertilized by means of the burning procedure.

and landscape development. It can be shown, that the availability of the non-finite resources timber, gathering grounds and livestock pasture is positively correlated with the continuous formation of a cultural landscape under a low-intensity land-use. The soil fertility is modeled in an external sub-model using the MONICA-procedure (Nendel et al. 2011) and is shown to decrease rapidly under NIC, to remain stable under SC and to react ambiguously under IGC and IFH.
None of the scenarios provided a strong argument for the necessity to shift a settlement consisting of 1-20 houses (6-120 persons) in the course of 100 years. However, the hypothesis that the spatio-temporal availability of suitable timber might have played a crucial role in the shifting of the settlements is supported by the model outputs. As the durability of the wooden house structures in wet environment is shown to be no more than 7-15 years (Ebersbach 2010), and a large quantity of wood is necessary for the construction (Petrequin 1991; Luley 1992), a suitable forest stand with easy-to-harvest timber in large quantities and the right dimensions would certainly have attracted the interest of people. With WELASSIMO, it can be demonstrated how ideal timber stands are a rare resource that is dynamic in space and time.

4.2 WSM: ñWorldò size society- driven models

Several attempts were made to extend the previous category of models to a global scale, with the necessity to answer the criterion (1): social & environmental spatial genericness. A possible way can be seen in (Meghan (2011), which assumes a specific theory (here: the circuit theory), and focuses on certain factors, movements of people in this case. Similar model attempts were built with the integration of demographic and social issues along environment, and natural resources and stresses as inputs and variable impacts on the population evolution and differentiation as outputs, such as one of the most achieved ones on ancient Maya (Heckbert 2013).
Another model was tried to be assessed for answering the three criteria we raised) for both the everyday life, including social, family and agro-ecological constraints, at the local scale and the population spatial and demographic dynamics at the global scale: The Obresoc project Boucquet-Appel et al. (2009) tries to reconstitute the expansion of the LBK culture throughout non-Mediterranean Europe, even beyond the regions where LBK archaeological remnants were found, in order to not artificially constraint the settlement process. This was possible thanks to the assumption that what was collected from archaeology on spots related to the same culture is valid for all the sites of the same culture, thereby assuming the genericness criterion (1) without tending to prove it. The World Climate project (Hijmans et al. 2005)provide the access to present-day climate data (temperature and rainfall), from which was roughly reconstructed the climate and its variability at that time, as described inSaqalli (2015): The palynology-based climate reconstruction of Ortu et al 2011provides the average Europe temperature and rainfall time deviations with present-day figures, while the World Climate project provides the statistical deviations both in terms of time (seasonal variability based on 50 years of data) and space (with a precision of 10 km x 10 km cells, transposed and adapted to 1ha-cell of the model). The work of Schwartz et al. (2011) was used for building the soil properties in the model, and Saqalli (2014)supplied the background for the farming and society system and variability. Processes of reactive adaptation were formalized but no cognitive nor selective appearance of technical or social innovations may occur, i.e. it does not fulfill the criterion (2). Finally, the conjuncture adequacy or inadequacy between time, society and space and the related emergence was considered as the model agreed that the driving force, humans, act at the local scale, following the modelling scheme of Saqualli (2014). This local driving force affects the dynamics at the global scale along the long era of the LBK culture thanks to the connection between access to natural resources and manpower availability, complying the criterion (3). Because the Europe-scale model encountered severe methodological and scale issues along its building process, mainly due to its computer requirements (320 millions of pixels treated sequentially four times a year (one time step = one season) along 800 years, with up to 4 millions of human household entities acting), this crucial connection between local and global scales was erased to simplify it but also for idealistic assumptions Renfrew (1987), thereby annihilating the emergence potential of this project.
More globally , hypotheses on the rationality that may have driven past societies should integrate the everyday constraints at the household level because it is at this very level that environmental, social and agro-ecological constraints are experienced differently from one household to another. Using present-time human socio-anthropology and especially theories of conflicting and limited rationality and planning, restricted information and interaction may be very useful for building a simple but acceptable cognition of the households. Acknowledging that all societies are not homeostatic may allow emergent properties in modelled rural societies, including "surprises", i.e. big expansion or total collapse without climate or other environmental constraints. For instance, the fact that family manpower should be actually seasonal and anthropologically restricted may have a huge impact on the productivity of such labour-constrained systems. Finally, the genericness point we raised may be partially reached through inference from ñexisting inferential frameworks (e.g., certain strands of evolutionary archaeology[2]) but that explicitly sociological simulation remains a challenge" (Lake 2014).

[2] We here include as well present-time originated anthropological theories.

5 BUILDING A GRID OF ANALYSIS FOR EXPANDING THE GENERICNESS OF A PAST SOCIETY-ENVIRONMENT MODEL

5.1 *Objectives for expanding model genericness*

One may point out that building a model that fulfils both scale & discipline categories (i. and ii. in §2) and temporal, spatial and emergence genericness criteria (1. 2 and 3. in §3.1) may be:

- Very difficult to build, both humanly and technically: it needs a lot of time to build a model with many disciplines, which means managing consortiums of thematic-oriented scholars for whom the value of a model depends on the spatial and temporal adequacy with their own data. Thereby, defining altogether within the consortium the model variables to consider but also to exclude, which is far more difficult, is a harsh task[3];
- Very challenging to validate: two validation steps are to be considered: confrontation with external data and sensitivity analysis (Amblard et al. 2006). As described by the latter and Bonaudo (2005), there is no absolute validation of a model. Following Popper (1985), a theory and therefore a model is temporarily accepted until it is rejected. Field data confrontation is challenging technically but not methodologically as far as a database was kept apart of the model building for confrontation purposes. On the other hand, sensitivity analysis complexity increases dramatically with the number of variables which are to be integrated in a model;
- Useful only under specific conditions: outputs of a very multidisciplinary model are harder to interpret for a monothematic scholar, meaning that the more a model is multidisciplinary; the more the use of it may be de facto restricted socially to modellers and the more publications are harsh to be published: journals are mainly thematic-oriented and model description increases with the number of disciplines, decreasing thereby their acceptance.

We can then deduce from these points that the ultimate goal of one modeller, at least for the present-time, is not to build the ultimate model that can answer and/or explore all the combinations of a past human-environment interaction.

Whatever the variable in a spatialized model, data are never fully and perfectly available, neither for present-time data and even less so for data concerning past periods. Such a perfect source cannot exist, once we acknowledge that spatial data can be completed only through reconstructions, at least partially, based on interpolations or inferences. Thereby, lacking data can be compensated by assumptions based on inference as well; The fact that data quality varies is not per se a criterion whether to use one type of data (and the corresponding variable and discipline) and to exclude another one. The sole criterion for deciding if a phenomenon should be included is the common agreement between scholars, even without data. Therefore and following Saqalli (2010), including a variable that is acknowledged as important, , is a smaller error than not considering it, even if this means to include it in a very simplistic way.

Finally, following An (2012) or Tzanopoulos (2013), models where disciplines are combined but also interact may produce emergence of unexpected phenomena. More globally, one cannot always define ex ante the impact range of many variables. This applies especially for social variables, such as availability of manpower dedicated to rural activities, which may have multiplied impacts over the transformation power of humans over natural resources. We thus identify the following two desiderata:

- A methodology of model combination to answer the requirements we proposed above;
- A guideline of models according to objectives and available data.

5.2 *Combining four objectives for expanding model genericness*

We then consider that analysing the validity of past society & environment models is performed as follows:

- Adequacy to scale and spatial genericness: simulation outputs correspond as much as possible to local data along time;
- environmental genericness: the model can be considered as reproducing correctly environmental dynamics of a broad territory;
- social genericness: the model is acceptable regarding social dynamics, including innovationsô appearances, adaptations and social differentiations;
- Validity regarding emergence: It includes conjunctions, emergences, shocks, sudden events that may impact evolutions of a system.

The four types of models we described in the previous sections may be categorized along these four genericness paths, following Table 1:

TABLE I. CRITERIA OF GENERICNESS FOR MODELLING PAST SOCIETIES AND THEIR ENVIRONMENTS

Model types	**Scale and spatial genericness**	**Environmental genericness**	**Social Genericness**	**Validity regarding emergence**
TEM	Yes: it is de facto an ñinstantanéò	No, because of the scale	No	No
TSM	Yes, with variations along scenarios. ex.: 1 scenario = 1 innovation	No, because of the scale	Yes, with drivers ruling innovationsôappearances or not, following theories	Yes, locally, thanks to social drivers. Environmental ones are less integrated because of scale

[3] Some co-modelling methodologies do exist such as ARDI [62]

WEM	No, too broad	Yes, even with huge simplifications	Yes, with drivers ruling innovationsôappearances or not, following theories[1]	No
WSM	No, too broad	Yes, through present time farming system inferences	No (not yet?)	Yes, socially and environmentally

Based on this classification, we propose a grid of pathways for expanding the genericness of the initial model one scholar may have built. Because each model is *de facto* a theory, i.e. a conceptualisation of a socio-ecological system (SES), it is also a methodology of test of this theory regarding scale, environment, society and emergence. Once a scholar has a model corresponding to one archetype we described in table 1, different ways for expanding its genericness start from the initial model and may follow different procedures according to the genericness objective the scholar may have, itself defined by the pursued research question. The Figure 4 illustrates the various patterns such pathways may follow.

These combinations of factors induces the definition of twelve pathways of genericness expansion, each one describing a methodology of model uses according to scales and drivers, each one allowing the exploration of one research question, that we described in Table 2. As a matter of fact, establishing a selection arborescence of procedures of combination and use of models according to different criteria (scale, disciplines as inputs and drivers, consistency principles, etc.) leads to so many combinations that a full arborescence is yet to be built.

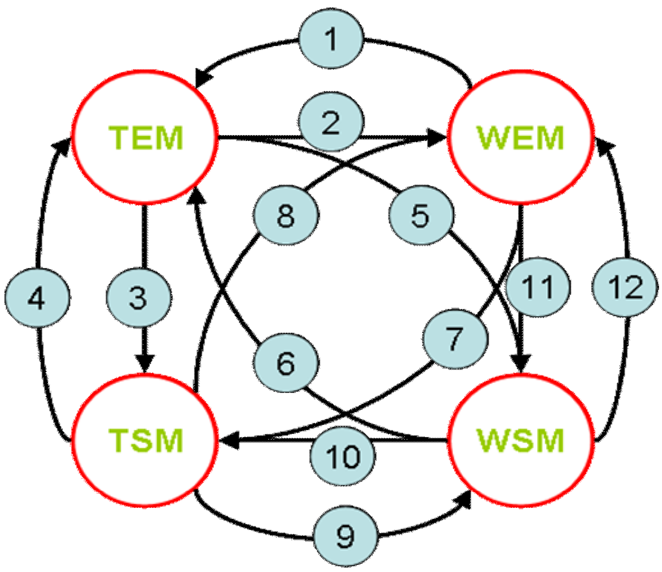

Fig. 4: Diagram of validity expansion paths, from one of the four model archetypes

TABLE II. PATHS OF GENERICNESS FOR MODELLING PAST SOCIETIES AND THEIR ENVIRONMENTS

Methodological procedure		Related research question
1	TEM→WEM procedure:	**Integrative world models improvement approach:** Step by step improving world models by including results from various local case study models
2	WEM→TEM procedure:	**World models Testing approach:** Analysing world models results for specific locations, to compare with results from local archaeologically-constrained models; Building first trials of local models, to be compared with archaeological data
3	TEM→TSM procedure:	**Local impacts of innovations/adaptations evaluation approach:** Using a TEM model as a test-bed for analysing innovations & adaptations to shocks ćosts/benefitsô not to compare with data
4	TSM→TEM procedure:	**Innovations appearance identification approach:** Several TSMs are tested to see if they fit better with archaeological data and TEM data: which innovations appearance and statistically-defined chaotic events explain farming system situation, sustainability AND diachronic evolution?
5	TEM→WSM procedure:	**Integrative world models improvement approach, including global shocks:** Step by step improving world models by including results from various local case study models AND integrating large scale variability (climate, for instance)
6	WSM→TEM procedure:	**World models Testing approach:** Analysing world models results for specific locations, to compare with results from local archaeologically-constrained models and timely constrained ñsnapshot modelsò; Building first trials of local models, to be compared with archaeological data
7	TSM→WEM procedure:	**Integrative world models improvement approach, smoothing local shocks:** Step by step improving world models by including results from various local case study models, including local variability & innovations
8	WEM→TSM procedure:	**World models Testing approach, including local shocks:** Analysing world models results for specific locations, to compare with results from local archaeologically-constrained models, including local variability to see if it is smoothed at large scale ;
9	TSM→WSM procedure:	**Integrative world models improvement approach, including shocks:** Step by step improving world models by including results from various local case study models, transferring local variability & innovations at a global scale
10	WSM→TSM procedure:	**World models Testing approach:** Analysing world models results for specific locations, to compare with results from local archaeologically-constrained but including innovations & shocks models;

		Building first trials of local models, to be compared with archaeological data
11	WEM→WSM procedure:	**Large scale Shocks impact evaluation approach:** Analysing impacts of shocks at a global scale by using a WEM model as a test-bed for analysing innovations & adaptations to shocks ócosts/benefitsô, not to compare with data
12	WSM→WEM procedure:	**Large scale Innovations appearance identification approach:** Several WSMs are tested to see if they fit better with archaeological data and WEM data (once one is settled): which innovations appearance and statistically-defined chaotic events explain farming system situations, sustainability AND diachronic evolutions?

Usually, choosing a model procedure depends practically on the availability of data: the more a model is global, the less such a system can be built along a systemic approach and the more it relies on paleo-environmental data, which are more or less the sole available at this scale. Thereby, the more the model is global, the more it tends to follow Malthusian environmentally-determined conceptions of human-environment interactions. We plea for avoiding this over-deterministic approach, chosen mainly for its practicability.

It means also to acknowledge that it is therefore important to start from the lower scale for avoiding this pro-environment prism but also to integrate archaeological information, which is the most conditioning information on SESs:

- The possible and plausible socio-anthropological societies, with no *a priori* consistency in its organization but solely in its functioning at the family level (whatever the organization of this last);
- The possible and plausible farming and environmental systems coming from inference from present-time non-mechanical farming systems, as well as the constraints and assets from its socio-anthropological organization as defined above and, its possible and plausible local ñterroirò-level biophysical characteristics. Agronomy and zootechny may establish the agriculture consistency at the local level along a systemic ñorganicò approach [50];
- The hazards, risks, and fluctuations at the same level (epidemics, plagues, family fluctuations) but also adaptation and resilience practices in present-time non-mechanical farming societies;

Transforming such a local model towards the global level implies trying to lose as less as possible the richness of the local scale, through:

- The simple iteration and juxtaposition of many ñterroirò models with inclusions of exchange procedures (goods, information, humans, etc.) between models, reconstituting the global level. However, this procedure requires huge computer capacities;
- The ñsmart simplificationò through the introduction of ñterroirò agents, each agent being built based on parameters established from a sensitivity analysis of several ñterroirò-like models, each one corresponding to a combined archetype of ecosystems and cultures. However, this procedure requires strong simplifications leading to an important loss of the emergence quality of the system.

The global level, once achieved, should acquire confidence, through:

- A confrontation with paleo-environmental data such as pollen databases;
- An independent territory reconstitution, through for instance GIS, purposely built for confronting its outputs with the ones from the model;

Finally and to conclude this formalization, we plea for acknowledging that a model is no more than a formalization of representations settled as a lab of experimentations:

- Its value is solely defined by a consensus among scholars;
- It has no value in itself apart from favouring the debate among scholars, formalizing scientific questions and exploring scenarios;
- It then can be used only as a test bed, through a plan of experiences, with series of scenarios, each one corresponding to a combination of alleles of several variables.

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